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# Protons on Target

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MI/Beams

## Goals

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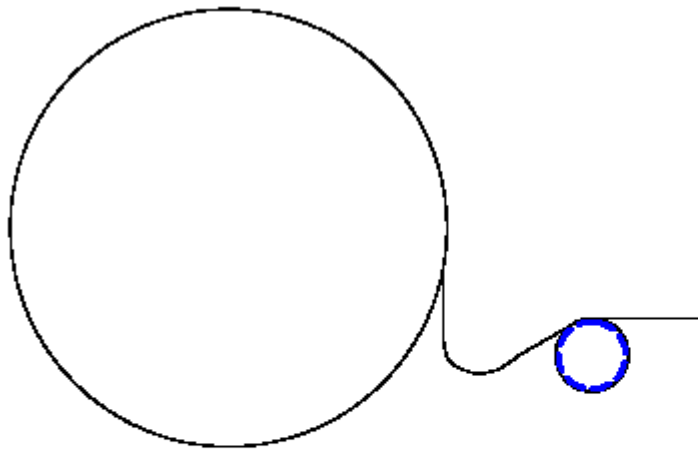
- Double the beam intensity on the antiproton production target (from  $4E12$  to  $8E12$ ).
- Limit the length of the stacking cycles to 2 sec (including 5 Booster batches for NUMI).
- Produce a bunch length on pbar target smaller than 1.5 nsec.
- Limit the transverse emittances of the beam on target to 25  $\pi$ -mm-mrad or less.
- Upgrade the antiproton production target to take full advantage of the increased proton intensity.
- All the above are expected to increase the current stacking rate by a factor of 2.0 (from present).

## WBS Summary

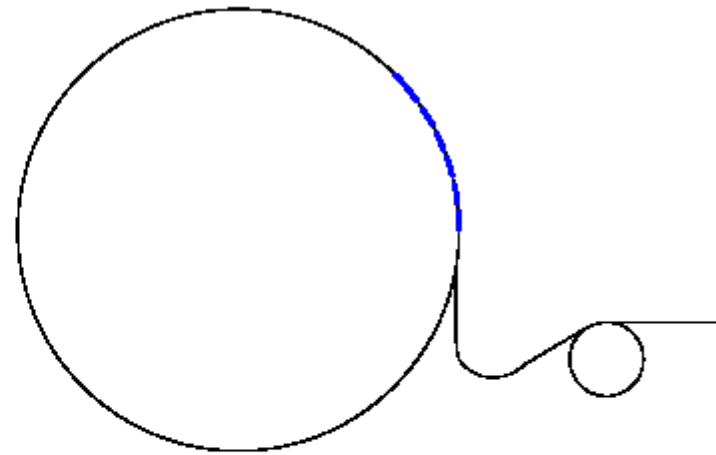
WBS	Task	In Charge	Labor Est (\$K)	Labor Cont	M&S Est (\$K)	M&S Cont	Start
1.3.1	Protons on Pbar Target	I. Kourbanis	1,366	52%	2,332	52%	1/1/03
1.3.1.1	Slip Stacking	R. Pasquinelli	300	39%	1,310	47%	1/1/03
1.3.1.2	Pbar Target and Sweeping	J. Morgan	112	49%	97	38%	4/1/03
1.3.1.2.1	Target	J. Morgan	21	42%	20	20%	4/1/03
1.3.1.2.2	Beam Sweeping system	J. Morgan	91	50%	77	42%	4/1/03
1.3.1.3	MI Upgrades	I. Kourbanis	900	56%	925	60%	8/1/03
1.3.1.3.1	MI Dampers	W. Foster	76	40%	0	0%	10/20/03
1.3.1.3.2	MI BPM Systems	B. Choudhary	602	57%	900	60%	6/4/04
1.3.1.3.3	MI 2.5 MHz Acceleration	C. Bhat	222	60%	25	60%	8/1/03
1.3.1.4	Booster-MI Cogging	W. Pellico	54	71%	0	0%	7/1/03

## Slip Stacking cartoon (1)

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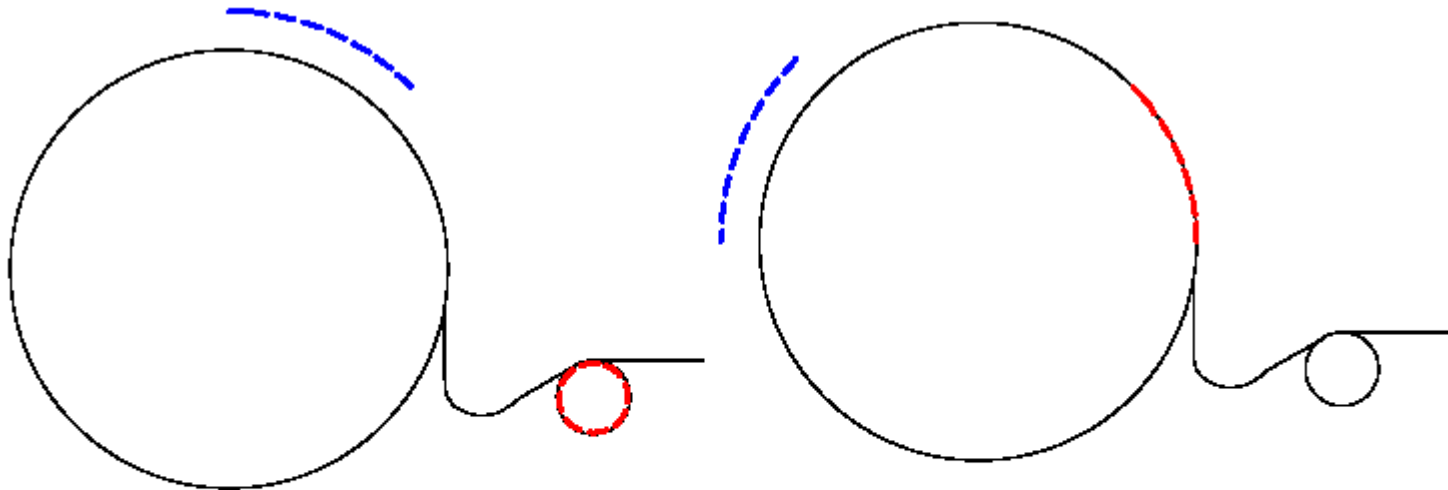
- First Booster Batch accelerated in Booster



- First Booster Batch injected onto MI central orbit with RF system A

## Slip Stacking Cartoon (2)

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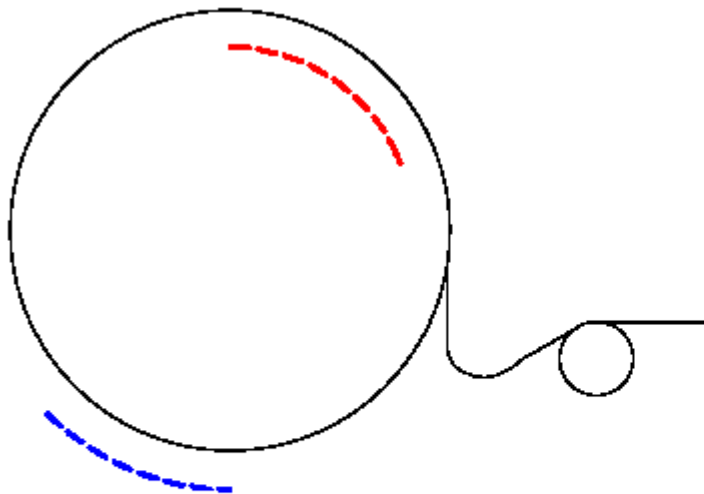


- First Booster Batch slightly accelerated in MI with RF System **A**
- Second Booster Batch accelerated in Booster

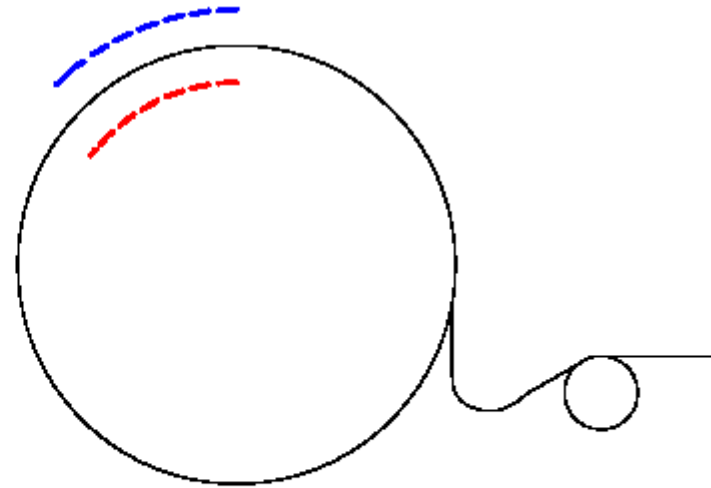
- Second Booster Batch injected onto MI central orbit with RF system **B**

## Slip Stacking Cartoon (3)

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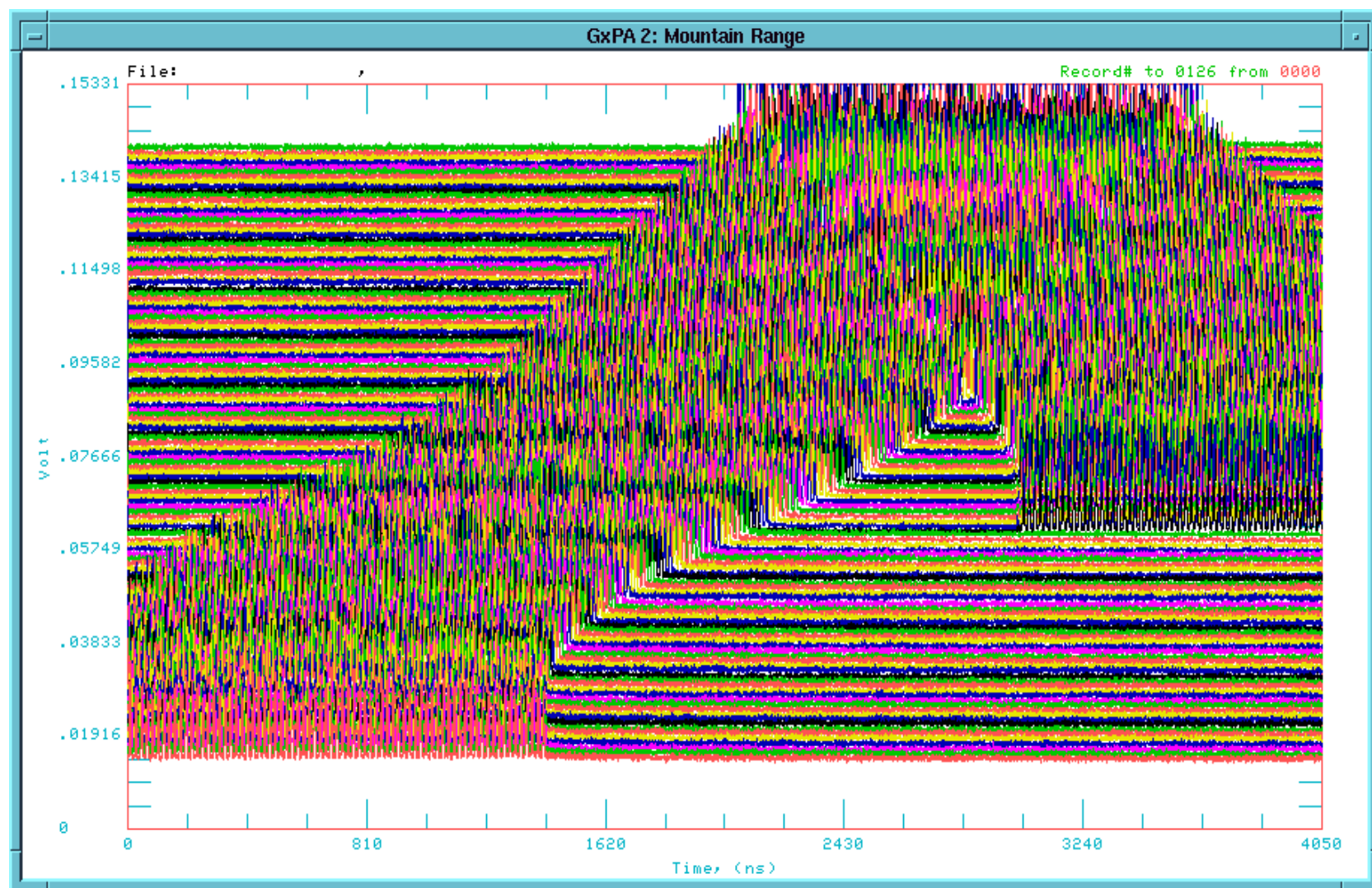


- Second Booster Batch slightly decelerated in MI with RF System **B**



- Wait till batches line up and snap on RF system **C** while turning of RF systems **A** & **B**

## Slip Stacking Mountain Range Plot with 1E12p

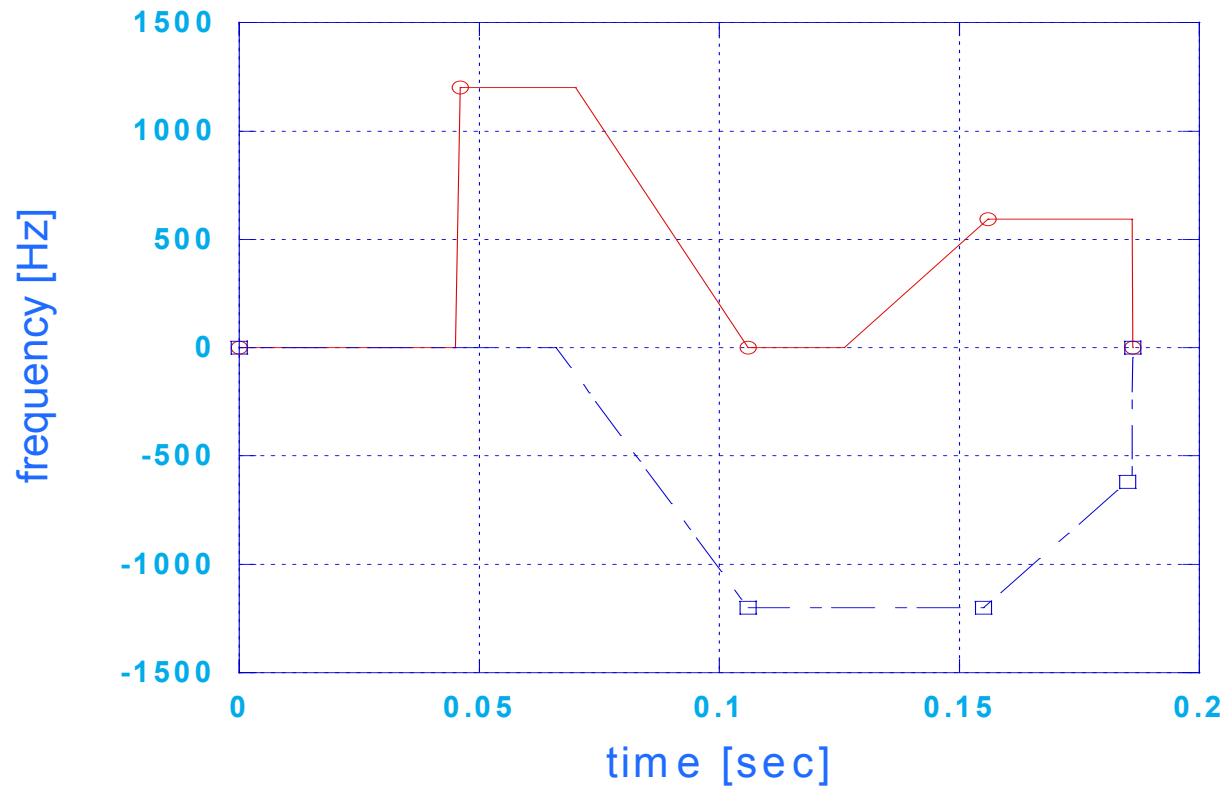


## Slip Stacking

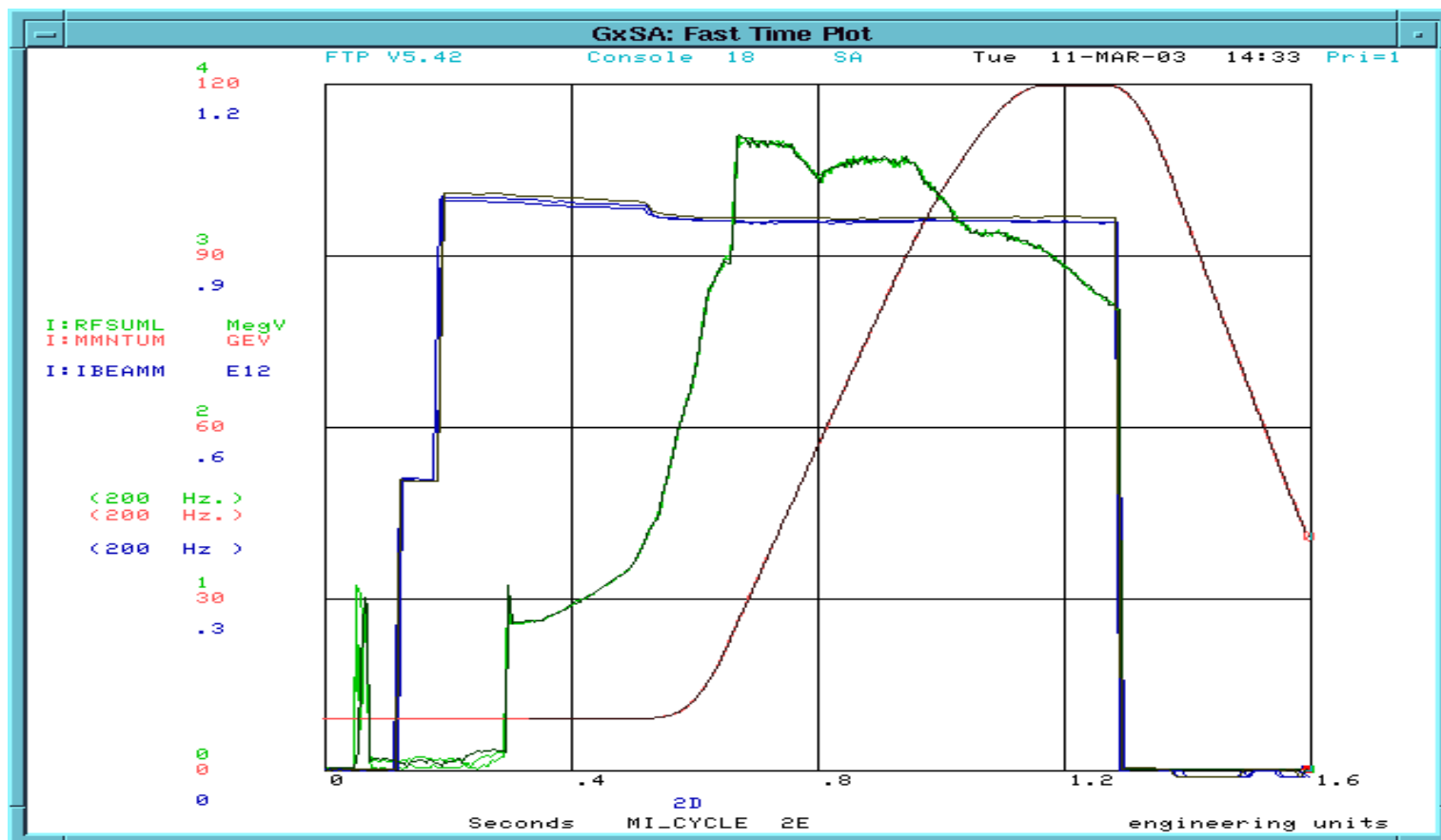
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- ❑ Slip stacking has been demonstrated successfully at low intensities ( $1.0E12p$ ) in the Main Injector.
- ❑ The slip-stacking efficiency was 98% and the final longitudinal emittance blow-up was a factor of 1.6 in agreement with the simulations.
- ❑ Most of the LLRF tools needed for slip stacking have been developed.
- ❑ The whole slip stacking process is completed in less than 0.133 sec (two Booster ticks).
- ❑ We have developed a beam loading compensation scheme that allows us to slip stack beam at high intensities.
- ❑ We have already accelerated half of our design beam intensity to 120 GeV.

## Slip Stacking Frequency Curves



## Acceleration of 1E12p to 120 GeV after slip stacking



## Beam Loading Compensation

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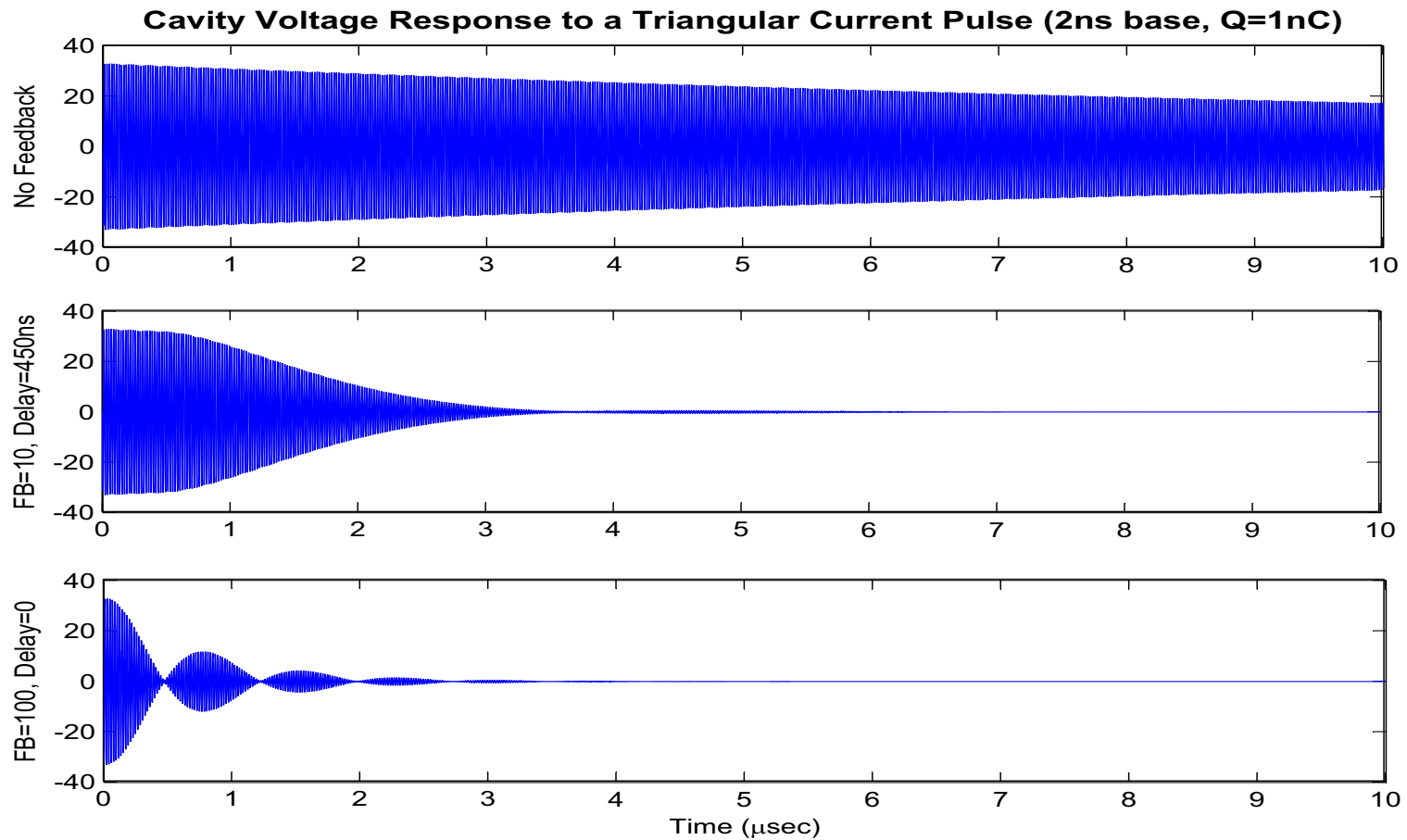
- Beam loading on the 53 MHz accelerating cavities is the biggest problem during slip stacking.
- From ESME simulations is determined that at least a factor of 20 (26 db) reduction of the beam loading voltage is required.
- We plan to achieve the beam loading compensation using a combination of feed-forward and feed-back.
- We are using a tube performance calculator in Matlab to analyze the performance of the Eimac Y567 cavity tetrodes tubes.
- We have developed a Matlab Simulink model to help us analyze the dynamic behavior of a single MI RF cavity with its control loops and beam-loading compensation loops. The cavity response to a triangular beam pulse is used as an input to the ESME simulation program.

## Beam Loading Compensation (2)

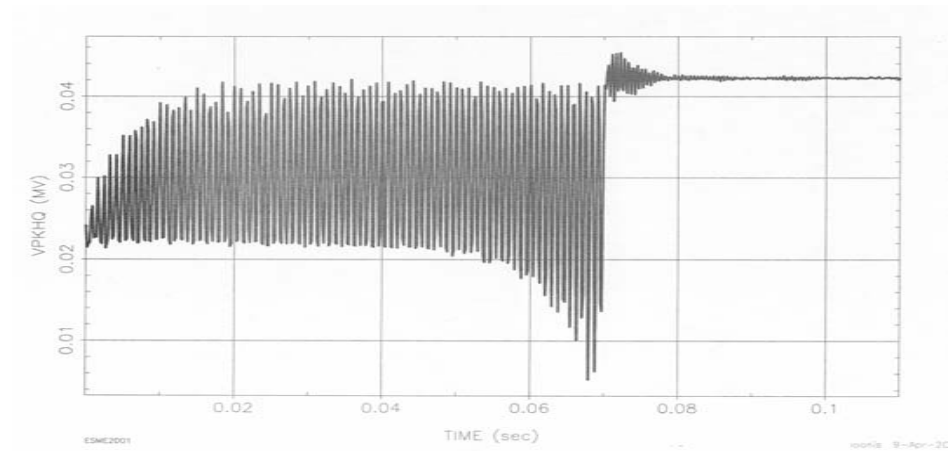
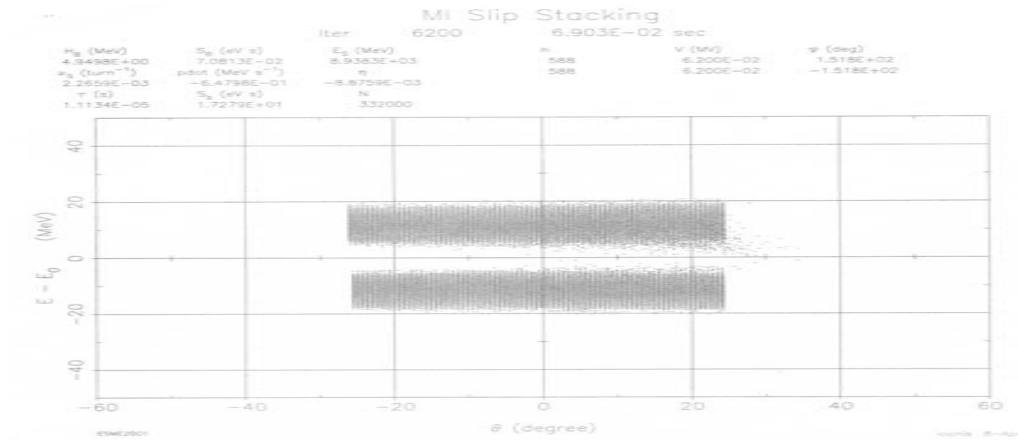
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- We are currently applying feed-forward compensation with a gain of 20-25db during both proton and pbar coalescing (total beam intensities of  $4E11$  or less).
- By changing the operation point of the final tube from class AB to class A in one rf station we were able we were able to achieve a total feed-forward compensation of 22 db (a factor of 12.6 reduction) during injection on the stacking cycles with total intensity of  $4.5E12$  ppp.
- We have determined that currently we have enough rf current available to supply the beam-loading compensation required for slip stacking up to intensities of  $8E12$  ppp.
- Additional solid state amplifier modules will be needed in order slip stacking to become operational.
- We have recently developed a scheme that allows us to apply feed-forward beam loading compensation during slip stacking with most of the rf stations off (no rf drive).

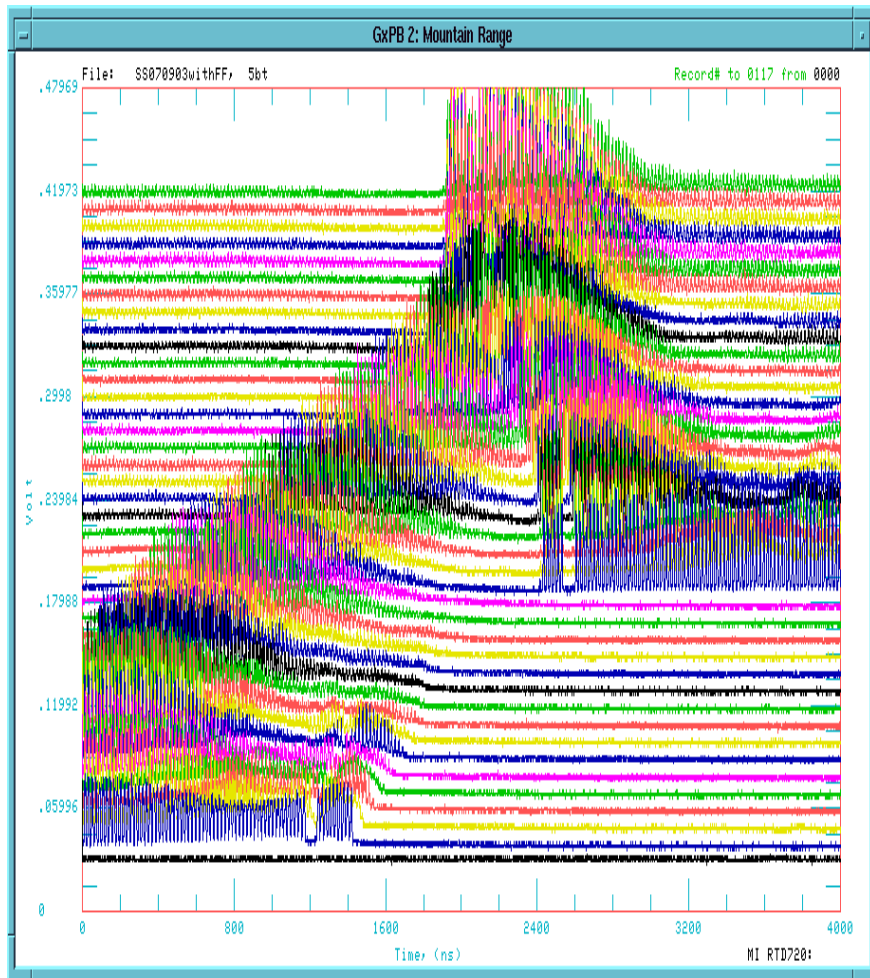
# Simulated cavity voltage response to a triangular current pulse for various system conditions.



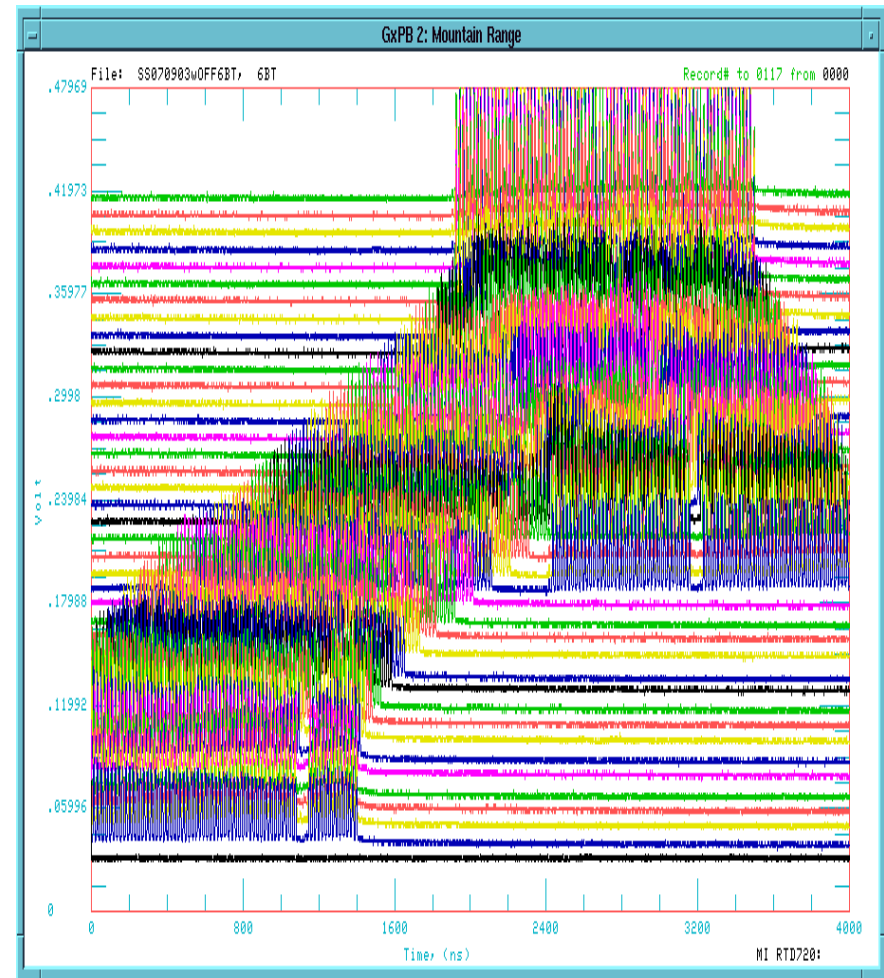
# ESME Simulations of slip stacking with 1E13p 20db of feed-forward and 14db of fundamental feedback.



# Slip Stacking mountain ranges with $5.2E12p$

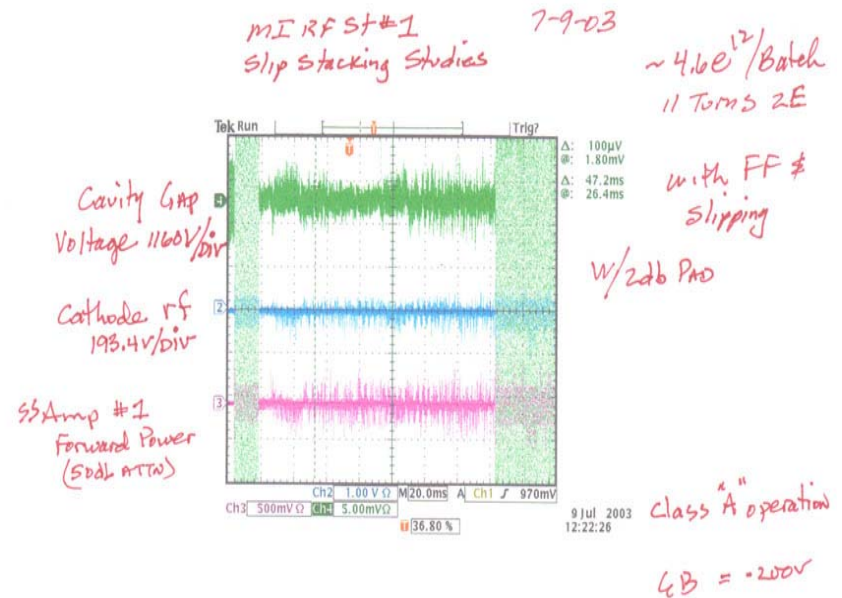
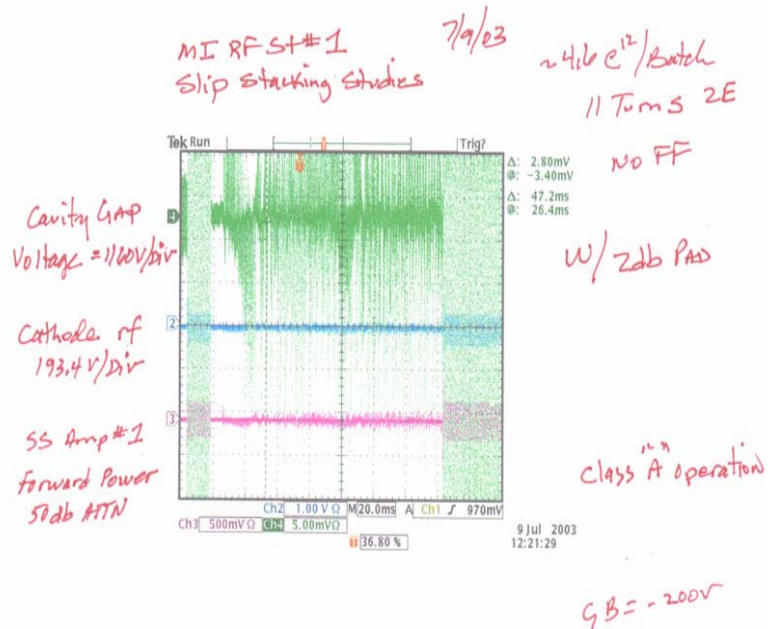


**Beam Loading Compensation OFF**



**Beam Loading Compensation ON**

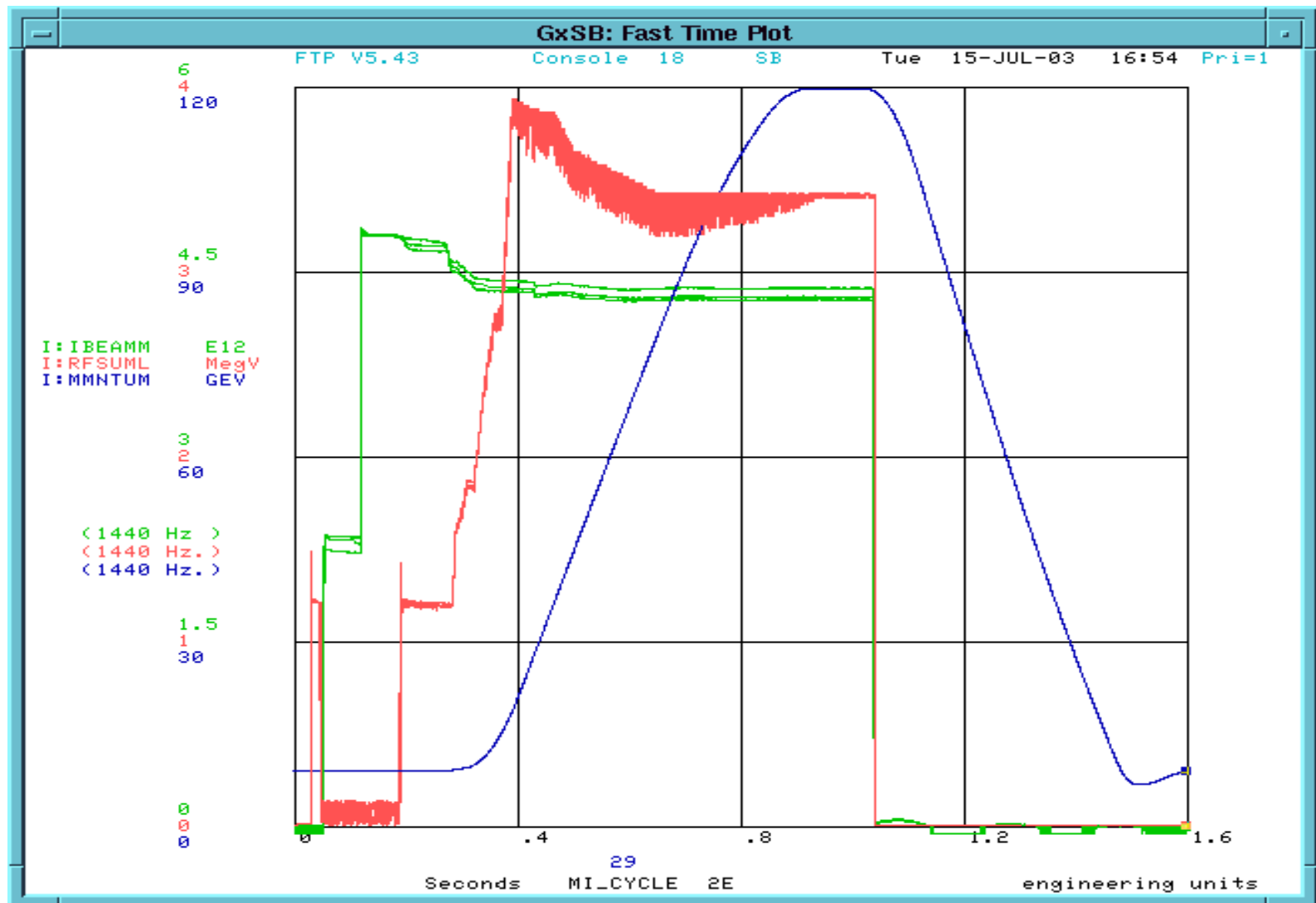
# Cavity voltage during slip stacking with no rf drive and 9e12p



Beam Loading Compensation Off

Beam Loading Compensation On

## Acceleration of 4.5E12p TO 120 GeV after slip stacking



## Other Beam Dynamics Issues

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- ❑ **Booster bunch rotations**
  - ❑ Beam in the Booster has to be rotated in the longitudinal phase space before extraction in order to match the low voltage (62KV) buckets in MI
  - ❑ Booster longitudinal mode dampers have to work at the highest intensities
- ❑ **Transition crossing in MI**
  - ❑ Transition crossing in MI is expected to blow-up the longitudinal emittance of the bunches by 30-35%.
- ❑ **Longitudinal Instabilities**
  - ❑ Couple bunch instabilities can dilute the longitudinal emittance of the bunches and affect the bunch rotation at 120 GeV needed to reduce the final bunch length at the target.
  - ❑ A bunch by bunch longitudinal damper is expected to be operational by the end of this year.
- ❑ **Transverse instabilities**
  - ❑ Bunch by bunch horizontal and vertical dampers are being commissioned.

## Pbar Target Energy Deposition and Beam Sweeping

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- The antiproton production target should be able to take full advantage of the increased proton intensity.
  - No reduction in antiproton yield.
  - Prevent local melting and target damage.
  - Maintain a beam spot size at the target of 0.1mm with larger transverse emittances.
- New target materials with same yield characteristics as the present target but better tolerances have been investigated.
- A beam sweeping system that moves the targeted beam during the 1.6  $\mu$ sec beam pulse has been constructed.
- Plan to develop beam-line lattice changes that will reduce the beta functions at the target so that  $\sigma=0.1$  mm in both planes with proton emittances up to 25 pi-mm-mrad.

## Pbar Target Energy Deposition and Beam Sweeping (2)

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- Inconel 600, 625, 686, X-750 and Stainless Steel 304 have been tested with beam and compared with Nickel 200. Based on the yield characteristics and resistance to damage Inconel 600 has been identified as the operational target material.
- The upstream target sweeping magnets have been installed in the tunnel and are ready to be tested. The downstream sweeping magnet is being completed and expected to be installed when the testing of the upstream magnets is finished.
- Recent beamline optics improvements have zeroed the dispersion at the target and reduced the spot size to  $\sigma_x=0.15\text{mm}$  and  $\sigma_y=0.16\text{mm}$  with transverse emittances of 19 pi-mm-mr.
- To achieve the goal of  $\sigma_x = \sigma_y = 0.1 \text{ mm}$  with a 25 pi-mm-mrad beam the beta functions at the target will need to be reduced an additional factor of two. New optics solutions will be modeled and tested with beam during the second half of 2003 to identify possible aperture problems.

## Target Reduction yield studies for different materials

Material	Spot size	Starting Yield	Ending Yield	Protons on target	Yield reduction scaled to $10^{18}$ protons
Nickel 200	$\sigma_{xy} = 0.15, 0.16$	1.000	0.970	$5.7 \times 10^{17}$	5.3%
Nickel 200	$\sigma_{xy} = 0.22, 0.16$	0.990	0.935	$6.6 \times 10^{17}$	8.3%
Inconel <sup>®</sup> 600	$\sigma_{xy} = 0.15, 0.16$	0.995	0.970	$10.6 \times 10^{17}$	2.4%
Inconel <sup>®</sup> 600	$\sigma_{xy} = 0.22, 0.16$	0.990	0.960	$10.7 \times 10^{17}$	2.8%
Inconel <sup>®</sup> 625	$\sigma_{xy} = 0.22, 0.16$	0.980	0.970	$6.6 \times 10^{17}$	1.5%
Inconel <sup>®</sup> X-750	$\sigma_{xy} = 0.15, 0.16$	0.985	0.965	$5.7 \times 10^{17}$	3.5%
Inconel <sup>®</sup> 686	$\sigma_{xy} = 0.15, 0.16$	0.970	0.935	$1.0 \times 10^{17}$	38.2%
Stainless 304	$\sigma_{xy} = 0.15, 0.16$	1.000	0.965	$6.1 \times 10^{17}$	5.8%

## Milestones

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1.3.1	Protons on Pbar Target	Ioanis Kourbanis	Date	
1.3.1.1.6	Design Review (Milestone)	R. Pasquinelli	9/22/03	C
1.3.1.1.10	Start Slip Stacking Assembly (Milestone)	R. Pasquinelli	2/9/04	C
1.3.1.1.13	<b>Slip Stacking Operational (Milestone)</b>	<b>J. Spalding</b>	<b>12/14/04</b>	<b>A</b>
1.3.1.2.1.4.3	<b>New Target in Operation (Milestone)</b>	<b>J. Spalding</b>	<b>12/30/03</b>	<b>A</b>
1.3.1.2.2.4.2	<b>Beam Sweeping Operational (Milestone)</b>	<b>J. Spalding</b>	<b>1/21/04</b>	<b>A</b>
1.3.1.3.2.2	MI BPM: Review (Milestone)	I. Kourbanis	8/4/04	C
1.3.1.3.3.2	Review MI 2.5 MHz Acceleration (Milestone)	C. Bhat	8/1/03	C

## Conclusions

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- Most of the tools required for slip stacking have been developed and the process has been demonstrated to work as expected at low beam currents.
- We have a beam loading scheme in place that allows us to slip stack beam at high beam currents and we have successfully accelerated half of our design beam intensity to 120 GeV.
- Both transverse and longitudinal dampers will be needed during the slip stacking cycles.
- We have identified a new target material for antiproton production.
- Beam sweeping magnets are ready for testing with beam.